CENTER FOR INTELLIGENT ROBOTIC SYSTEMS FOR SPACE EXPLORATION (CIRSSE)
SECOND SEMI-ANNUAL RESEARCH REPORT
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I. INTRODUCTION

This is the Second Semi-Annual Report, summarizing the technical activities of Rensselaer's Center for Intelligent Robotic Systems for Space Exploration, a NASA University Center of Excellence, covering the period between January through August 1989.

This period was a major organizational effort, with focus on the purchase and installation of the Laboratory's SUN computer network, composed of six SUN workstations and its peripherals interconnected with the VAX 11/750. In addition, the Robot Transporter (as shown in the figure at the end of this section) was designed for the testbed of our experiments for space assembly, disassembly and maintenance. A December 1989 delivery date has been scheduled.

There has been an increase in the number of students, from 31 to 35, involved in this Second Semi-Annual Report. This was the result of active recruiting of the faculty involved. Three of these students have been granted NASA Fellowships and there are several more financially supported by various fellowships as well as Rensselaer's Provost Office. The recruitment for the Fall 1989 semester looks equally successful, since more than 80% of the offers extended to United States students applying to Rensselaer have been accepted.

In addition, 24 research projects have been developed with the assistance of 35 graduates and undergraduate students. Project status reports are presented in the next section.

During the past year, Dr. John Wen was hired as an Assistant Professor of the Electrical, Computer and Systems Engineering Department after spending three years at the Jet Propulsion Laboratory where he worked in the control of flexible space structures and the control of multiple robot manipulators. Professor Wen is now a member of the CIRSSE research team. The research group also appointed Professor Alan Desrochers as the Associate Director of CIRSSE due to the growth of the Center.

The NASA Open-House was organized by CIRSSE, with the support of Rensselaer's Provost Office, on March 7-8, 1989. There were 40 people from

NASA, Industry and Universities. The meeting was considered very successful, since several topics of common interest were identified and discussed. A copy of the Open-House Program is included at the end of this section.

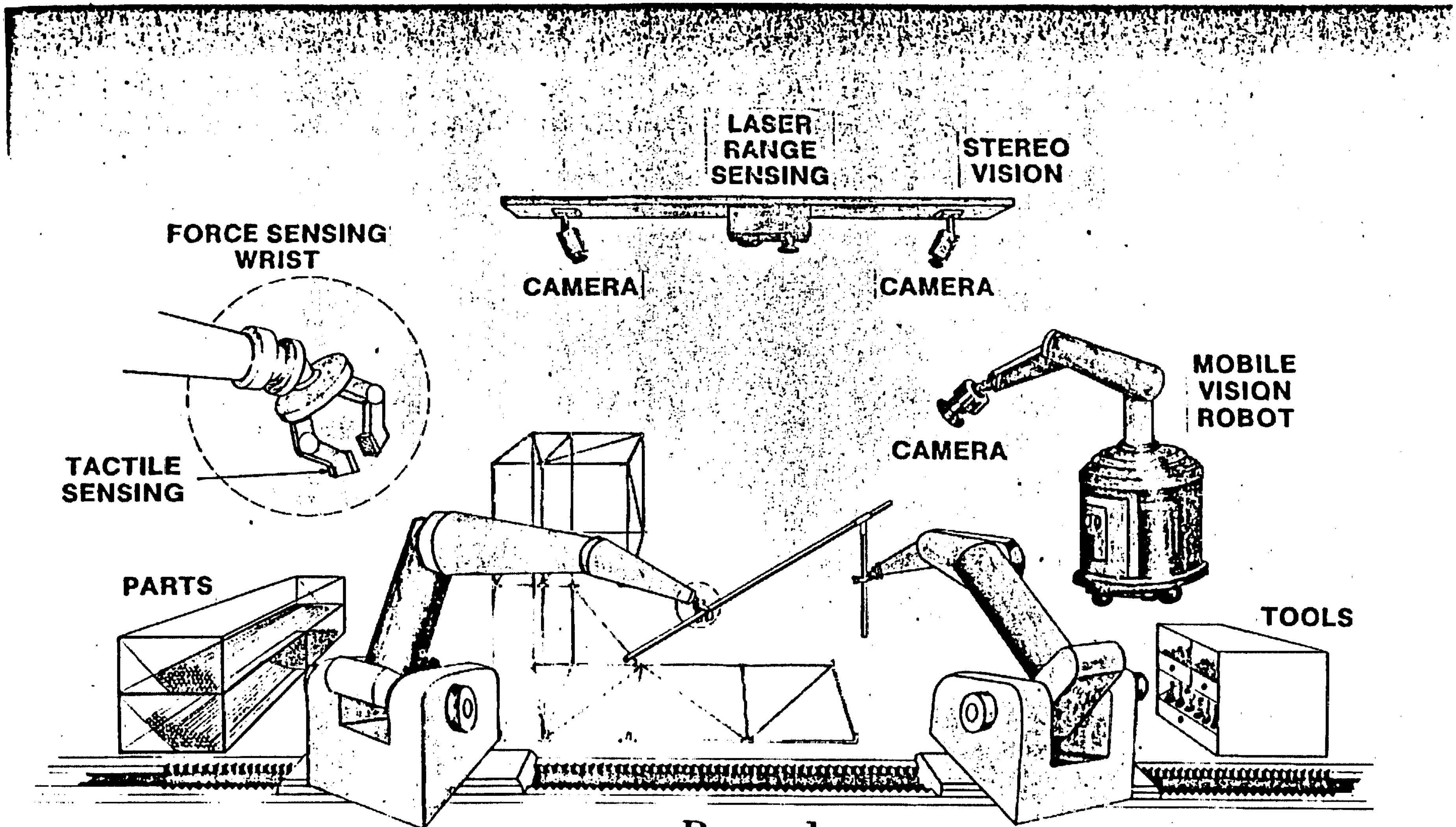
Interactions with industry were originated at the Open-House and are progressing slowly. The Center is presently involved in discussions with Grumman, a New York State based company, to identify projects of common interest.

The publication of this report coincides with the Annual CIRSSE Workshop which is scheduled for September 27, 1989, as a sequel to the Fourth IEEE International Symposium on Intelligent Control. Approximately 150 people from NASA, NASA University Centers, Industry and Universities have been invited to attend.

A list of the visits to our Center as well as visits of our faculty to NASA Centers is reported in Section IV. These visits have been extremely fruitful, because they have identified tasks of interest to NASA, like the assembly of large truss structures in space that have become a focal point for the research activities in CIRSSE.

In summary, the Center has positioned itself, in both staff and facilities, to continue to meet the research goals outlined in the original proposal.

George N. Saridis
Director, CIRSSE



Rensselaer

CIRSSE LABORATORY

ROBOTIC ASSEMBLY OF IN-SPACE STRUCTURES

fig 2

Center for Intelligent Robotic Systems for Space Exploration

CIRSSE

AGENDA

"A DAY WITH CIRSSE"

MARCH 7 AND 8, 1989

Tuesday, March 7, 1989 - The Desmond Americana in Albany

5:30	Bus Transporation from Troy Hotels to The Desmond	
6:00 p.m.	Registration & Cocktails	
6:45 p.m.	Welcoming Remarks	James Meindl, Provost Senior Vice President, Academic Affairs
7:15 p.m.	Dinner	
8:30 p.m.	Affiliates Program	Lester Gerhardt, Director Affiliates Program
9:15 p.m.	Bus Transportation to Hotels	

Wednesday, March 8, 1989 - Center for Industrial Innovation, 4th Floor

8:30 a.m.	Continental Breakfast	
8:45 a.m.	Welcome to RPI	Roland Schmitt, President
9:00 a.m.	Technical Presentations	
10:20 a.m.	Morning Break	
10:50 a.m.	Technical Presentations (Continued)	
12:30 p.m.	Lunch	
	Introduction to Affiliates Program	Lester Gerhardt Director, Affiliates Program
2:00 p.m.	Tour of Facilities and Demonstration	
3:00 p.m.	Future Directions of Space Robotics Research	Mel Montemerlo, NASA Headquarters
3:30 p.m.	Afternoon Break	
3:45 p.m.	Wrap-Up	George Saridis Director, CIRSSE

II. PROJECT STATUS REPORTS

A. THE MATHEMATICAL THEORY OF INTELLIGENT CONTROL

PROJECT 1: Petri Nets for the Coordination Level of Intelligent Machines
F.Y. Wang and G.N. Saridis

A theory for the coordination level of Intelligent Machines was developed using an analytical model called *coordination structure* (see Figure A-1). *Petri net transducers* (PNT) are used as the basic module to implement *linguistic decision schemata* previously used for modeling and analyzing the task translation and task execution in the coordination process in the coordination level of Intelligent Machines. The cooperation and connection among the dispatcher and the individual coordinators in this level is specified by the *synchronous composition* of PNTs and the *receiving* and *sending maps* of the coordination structure. The analysis of the process is achieved within the context of Petri net theory where various new concepts and procedures are developed for Petri nets to serve the purpose of coordination of tasks. Moreover, process evaluation like the average execution time can be performed by using timed Petri nets. The execution rule of Petri nets provides the base for designing a task scheduling procedure and a learning algorithm gives an updating method for finding the optimal task translation in the uncertain environment. This model of coordination provides an analytical mechanism of control and communication at the coordination level of autonomous Intelligent Control Systems applicable in various fields of modern industry such as Intelligent Robotic Systems and Computer Integrated Manufacturing Systems.

A case study of modeling the coordination level of an Intelligent Robotic System using the above theory of Intelligent Machines was conducted. The coordination structure designed, consists of a dispatcher, a vision coordinator, a sensor coordinator, a path planning coordinator, an arm coordinator, and a gripper coordinator. Petri net transducers characterizing task plan translation and task scheduling for the dispatcher and the rest of the coordinators are described. The coordination structure is constructed by integrating the dispatcher and coordinators through the specification of their connection and cooperation procedures. Task simulation based on the coordination structure is performed with various task plans for the system to investigate and evaluate the coordination processing in the System during task execution. Figure A-1 demonstrates the coordination structure model which provides an effective mechanism of control and communication for the simulation and real-time monitor of the task processing in the coordination level.

The case study is the first step toward the construction of a complete analytic model for the coordination level of an Intelligent Robotic System.

The current model has offered an effective mechanism of communication and control for coordination, an overall control formulation is still desired for the coordination structure. Such overall control formulation should be capable of guiding the dispatcher and coordinators work cooperatively but with individual performance criterion. The team-theoretic formulation seems to be the most promising one for serving this purpose. Research along this direction will be the focus over the next year.

PROJECT 2: Path Planning for an Intelligent Robot by the Extended VGraph Algorithm

C.H. Chung and G.N. Saridis

In the configuration space of path-planning algorithms, the moving object is shrunk to a configuration point, while the stationary obstacles are expanded to fill all space where the presence of the configuration point would imply a collision of the object with obstacles. Therefore, the *Findpath problem* can be formulated as a graph-searching problem. The graph is formed by connecting all pairs of visible vertices of the configuration space obstacles, which are defined as geometric objects that represent all the positions of the moving object that cause collisions with the obstacles.

Consider the *VGraph Algorithm* for a moving object to find the collision-free shortest path in a workspace with some obstacles. A lot of work has been done in this field, which has the following design steps:

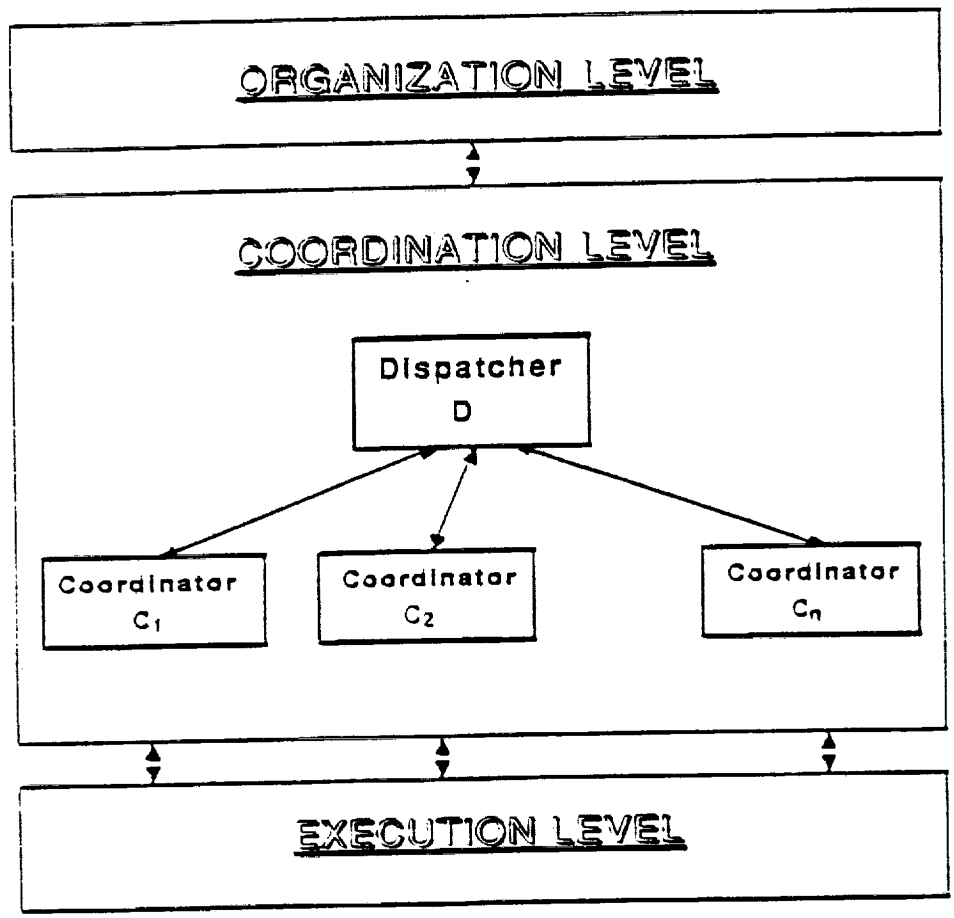


Figure A-1 The Topology of the Coordination Level

- Build the configuration space obstacles.
- Find the visible vertices by detecting interferences.
- Build the *VGraph* with a set of the visible vertices.
- Search the *VGraph* by the graph-searching algorithm.

The shortest path from the start to the goal in the *VGraph Algorithm* is the shortest path among the obstacles in 2D. However, the path in 3D by the *VGraph Algorithm* whose node set contains only vertices of the configuration space obstacles is not guaranteed to be the collision-free shortest path, because the shortest path may involve going through points on the edges of the configuration space obstacles in 3D. Lozano-Perez points out the drawbacks of the *VGraph Algorithm.* The first drawback is related with the rotation of a moving object. Since the *VGraph Algorithm* requires moving an object along obstacle boundaries, shortest paths are very susceptible to inaccuracies in the object models. This drawback has been solved by using the *sliced projection method.* However, the *VGraph Algorithm* has serious drawbacks when the obstacles are three-dimensional. Hence, the *Extended VGraph Algorithm* is presented to solve the drawbacks of the *VGraph Algorithm.* The *Extended VGraph Algorithm* has the following design steps:

- Apply the *Orthogonal Projection Method* to get the Grown Space Obstacles.
    1. Project obstacles in 3D onto the projection spaces.
    2. Build the Grown Space Obstacles in 2D.
    3. Select the necessary Grown Space Obstacles for the *VGraph.*
    4. Reconstruct the Grown Space Obstacles in 3D.

- Apply the sliced projection method.

- Find the visible vertices by detecting interferences.

- Build the *VGraph* with a set of the visible vertices.

- Search the *VGraph* by the graph-searching algorithm.

- Apply the *Recursive Compensation Algorithm* to obtain the collision-free shortest path in 3D.

Chung and Saridis proved that the sequences generated by the *Recursive Compensation Algorithm* are *Cauchy sequences.* Therefore, the number of recursive compensation could be calculated if the accuracy is known, or the accuracy could be calculated if the number of recursive compensation is given. Since the accuracy is defined by ε whose value is set to be very small and n is the number of obstacles in a given workspace, the *Recursive Compensation Algorithm* needs smaller memory space to store $(2 + 8 \times i)$ vertices for the *VGraph* with polyhedrons, than Lozano-Perez's alleviation method which needs a lot of memory space to store $(2 + 8 \times n \times \varepsilon_{-1})$ vertices for the *VGraph.* The *Extended Vgraph Algorithm* has the following advantages:

- It makes the *VGraph* simpler than any other algorithm, since the *Orthogonal Projection Method* avoid building the unnecessary *Grown Space Obstacles.*

- It can deal with not only translations of a moving object but also its rotations by the *sliced projection method.*

- It solves the drawback of the *VGraph Algorithm* when the obstacles are three-dimensional.

- It is proved that the *Recursive Compensation Algorithm* always converges to the collision-free shortest path.

- It has a fast convergence ratio.

- It can save not only the memory space to represent the *VGraph*, but also it can save the graph-searching time of the *VGraph.*

PROJECT 3: Boltzmann Machines for the Organization Level of Intelligent Machines

M.C. Moed, S. Miller, G.N. Saridis and R.B. Kelley

The research is patterned after the upper level of the Intelligent Machine as proposed by Saridis. the Organizer is a high-level planner which devises plans to achieve a user-defined goal based on the optimization of an analytic criteria. It must organize a set of abstract rules or primitives to develop these plans through the use of inductive or inferential reasoning.

The architecture of the Organizer combines both symbolic and connectionist theories. A connectionist network similar to a Boltzmann machine is used to develop a semantic interpretation for the probabilistic interaction of primitives in rules. The rules are symbolic strings which model cause/effect pairs with actions to be taken by the lower levels of the Intelligent Machine.

A performance value is assigned to each rule which relates the difficulty of or complexity of executing the rule. A probability value is assigned between the rule and its effect, allowing the system to model perturbations in the environment. A plan is formulated by finding the least complex, most probable sequence of rules which achieve the given goal.

Higher level functions in the Organizer allow generalization of known rules to other plans. Further, a second Boltzmann machine is used to generate rules which extend the exploration capability of the Intelligent Machine. Using a search technique such as Simulated Annealing or a Genetic Algorithm with guaranteed convergence, it is possible to discover low complexity, highly directed rules which drive the plan toward a given goal.

The research proposes the theory behind the Organizer, provides several informative examples, and presents simulations to validate certain theoretical concepts. Also in progress is an actual case study based on this theoretical structure. The case study will focus on modeling the construction of trusses into geometric shapes and testing the ability of the Organizer in planning a construction when trained on a simulator.

B. MULTISENSOR FUSION

PROJECT 4: Velocity Estimation from Distorted Image Sequences
E. Simpson and H. Kaufman

Estimation of object motion in an image sequence is important for the development of commands to an autonomous robotic controller. Such motion can be described by velocity fields that can be estimated using region matching, least squares, optimization, and maximum likelihood procedures. However, if the image of the object is blurred and/or noisy then severe errors can be introduced unless some type of restoration is incorporated.

To this effect, a study is being made of the benefits of incorporating two dimensional Kalman filtering techniques into the velocity estimation procedures. Possibilities include the prefiltering of the images prior to the velocity estimation, postfiltering of the velocity field as estimated from the original sequence, and a model based procedure that directly relates sequence differences to the velocity field.

Towards these goals a user interactive restoration program is being developed for the SUN System with the SUNVIEW programming package.

SUNVIEW is the windowing environment used by the SUN's for creating windows, panels, menus, etc., for allowing user input to programs. This image processing software is based on a program called Imagetools, written by Dr. Michael Norman and Carol Song at the University of Illinois. The program will be able to degrade images for controlled restoration experiments, identify image model parameters, filter images, and calculate velocities for sequences as previously described. In addition, the program will provide basic routine for the display and saving of images, zooming, graphing, sequence animation, and grey-scale palette modification.

PROJECT 5: Lord LTS-200 Tactile Sensor
S. Sekelsky and R.B. Kelley

An attempt was made to characterize the Lord LTS-200 Tactile Sensor. The results of the tests show that the sensor has limited usefulness. This is due to both the inferior mechanical performance of the sensor and the designed-in limitations of the interface/controller. Some improvement in edge location is possible through the use of deblurring filters to compensate for the smearing introduced by the protective membrane. The built-in coarse quantization and other non-linear effects such as hysteresis impose severe limitations on the effectiveness of such techniques. The sensor interface would have to be redesigned to separate the intrinsic device limitations from the artifacts of the compromise controller design.

PROJECT 6: Sun-Based Vision System
D. Sood, M.C. Repko and R.B. Kelley

A TAAC board and a Matrox vision board was installed in a SUN workstation. The software was installed and fully tested. This vision system will supply visual sensing needs for the control of the dual arm system. M. Repko is presently implementing a stereo matching algorithm which uses the overhead camera system, the TAAC board and the Matrox board. He is also conducting a literature search on stereo matching algorithms in preparation for future research. Stereo matching will provide 3D feedback for robot control.

PROJECT 7: Lord Wrist-Torque Sensor
D. Sood, M. Repko and R.B. Kelley

This sensor will provide the basic contact-generated information used for robot task control feedback. To enhance the integration of force-torque into smart systems, a task-generic interpretation of force-torque sensor information has been proposed. This interpretation is used to provide correction inputs to the robot controller. The current implementation is based on fuzzy logic and, hence, is referred to as a Fuzzy Controller.

The sample problem domain which was explored was the insertion of printed circuit cards, as in a module repair scenario. The insertion process was characterized as consisting of four phases: precontact, guide insertion, guided insertion and card seating. Fuzzy rules were developed for each of these phases as well as rules to determine which phase was active. Near-miss error recovery behavior was demonstrated for purposely introduced error conditions.

M. Repko and D. Sood ran physical experiments with the vision system and robots, took data and refined the fuzzy logic set and rule definitions. Papers were written and presented at the 1989 NASA Space Telerobotics Conference held at Jet Propulsion Laboratory and the 1989 IEEE Conference on Robotics and Automation held in Scottsdale, Arizona. An additional paper was written for a special issue of the Journal of Robotic Systems.

C. TASK PLANNING AND INTEGRATION

PROJECT 8: Task Planning Integration
S. Derby

We have investigated a specific approach to the multiple arm path planning/collision avoidance/manipulation problem based on the previous work of Pierre Dupont. His path planning algorithms, for a single seven jointed robot, were themselves efficient, but his use of Octrees as a solid modeler was a real bottle neck.

The Octree solid modelling interference checking was replaced by a Polytope approach. While inherently approximate, this method was adopted for its high speed. The robot and obstacles are represented as unions of polytopes. A simple approximation to swept volume is used with a distance function to check for interference.

Table C-1 demonstrates the increased efficiency of the polytope approach over that of the Octree. The resulting speed will allow for reasonable two arm manipulation research.

Voxel Edge Length = 5° Total Number of C-space Voxels > $2 \cdot 10^{12}$		
	Phase 1	Phase 2
Number of Voxels in Path	114	200
Number of Voxels Checked for Interference	119	235

CPU Time (Phases 1 & 2)		
	Polytope Method (Sun 4)	Octree Method (μVAX II)
Interference Checking	23.27 seconds	25 hours, 19 minutes
Planning Algorithm (μVAX II)	1 minute, 22 seconds	
Total Time	1 minute, 45.27 seconds	25 hours, 20.3 minutes

Table C-1. Example Performance Data

We have continued to work with Dupont's algorithm as the main thrust for multiple robots. The kinematics of two robot arms at any static location is rather trivial. It is the time varying locations and paths of two or more robots that is the research, and the method of representing these arms the as the important tool.

We are purchasing a SUN SPARC workstation to continue the work. The combination of the Dupont algorithms, the polytope representation, and the SUN workstation should make for a very fast and powerful system.

PROJECT 9: Reasoning About Assembly Plans
H. Welch and R.B. Kelley

H. Welch is exploring issues encountered in the analysis and reasoning of assembly plans in the absence of robot-specific information. This level of abstraction is appropriate for the strategic level of analyzing and refining plans by concentrating on WHAT has to be done rather than HOW it is to be accomplished. Such plans are designed to be transferable among a family of implementations.

The relevant subproblems include motion planning, stability analysis of partial assemblies, grasp site planning, partial assembly inspection and verification, and specification of the permitted gripper envelope. The gripper envelope is derived through an analysis of the motions which are made by the subassemblies during an assembly step. The volume which is not swept by the subassemblies is available for the unspecified gripper and its fingers. This analysis allows the constraints imposed by a particular assembly on the choice of gripper. Clearly, if there are competing assembly sequences, the sequence with the fewest gripper constraints might be preferred. In addition, this analysis can be performed without regard to the additional consideration of the arm and other structures in the work volume.

PROJECT 10: Collision-Free Trajectory Planning
S. Bonner and R.B. Kelley

S. Bonner has been exploring a novel representation for planning 3D paths. The representation is based on a sphere-based hierarchy which allows objects which are at a safe distance from the proposed path the quickly identified. Experiments indicate that this representation reduces the time to find a collision-free path by a factor of 3 to 20 over a planar face object representation. In contrast to the more familiar octree or configuration-space representations, the representation is easily manipulated to accommodate orientation changes required for obstacle avoidance in a cluttered environment.

PROJECT 11: Task Planning and Integration
R. Mathur and A.C. Sanderson

We have continued to develop a formulation of a planning network based on the AND/OR graph representation of plans. This AND/OR graph network is an extension of our work on AND/OR graph trees in assembly planning. The AND/OR graph provides an efficient representation of geometric and mechanical states, and permits a convenient problem decomposition which lends itself to search techniques. While most domain independent planning techniques are based on purely symbolic or propositional representation of world states, the AND/OR graph decomposition incorporates a hierarchy of geometric and mechanical representations and facilities reasoning about more complex states and attributes.

During this period we have focused on the application of these planning techniques to spaceframe assembly problems. Based on our interactions with the NASA/Langley Center, we have identified the problem of sequence planning for the assembly of complex space frames as a key issue for both human and robotic assembly of these structures. The key goals of this assembly problem are to successfully assembly a set of struts into a rigid spaceframe structure, while at each step the placement of a strut is geometrically feasible and also all of the intermediate states of the structure are structurally stable. This problem fits into the framework which we have developed for sequence planning, and we are currently implementing software which will derive these sequence plans.

D. MULTI-ARM MANIPULATION

PROJECT 12: Coordinator Design for Real Time Navigation and Object Collision Avoidance of Mobile Robots
K. Kyriakopoulos and G.N. Saridis

The problem is initially stated as a motion replanning problem on the cartesian off-line preplanned trajectory. Later, the navigation problem is going to be considered based on more general type of information. The algorithmic path search problem is not going to be considered by this on-line scheme but only the on-line trajectory planning problem to give solutions to the dynamic changes of the environment. The following issues have been stated and investigated.

- Objects model representation: Objects are modeled as convex polyhedra.
- Performance analysis for several norms used as distance metrics between objects in cartesian space.
- Stochastic version of the above issues. The noisy information of the sensory devices lead to uncertain object representation and minimum distance. Optimal values for the lower bound of distance measures can be obtained.
- Kinematic information of moving obstacles has to be obtained in order to predict future collisions. The noisy nature of the measurements necessitated the use of a version of the Kalman Filter.
- Prediction of the collision time between the mobile robot and the moving obstacle can be done fast, by a modified version of the Accelerated Expanded Subinterval Random Search method.

- The collision avoidance problem has been stated in the form of an optimal control problem with space constraints that are affine functions of time and input (torque) constraints for the mobile robot.

The following issues are under research and are to be completed by the end of the year.

- Numerical solutions of the above optimal control problem. Convergence time evaluation. Parallel versions or suboptimal solutions.
- Extensions of the motion replanning strategy for the case where the cartesian path is not defined, but only specific set points to guarantee a solution to the "find-path" problem. In this case a manifold of free space is to be considered.
- Extensions to "busy" environments of numerous moving obstacles.
- Definition of the functions of the constructing blocks of the motion planning and a simplified version of the vision coordinator. Definition of the in between information transfer and the feedback information (reliability, complexity) upwards to the dispatcher. Performance analysis based on the petri-net model of F. Wang. (This item is common research with F. Wang).

PROJECT 13: Performance Analysis of The CIRSSE Testbed Control Architecture

J. Robinson and A.A. Desrochers

The successful operation of complex interconnected systems is heavily dependent upon the acquisition, transmission and processing of data in the form of information, knowledge and control commands. This requires an integrated approach to handling control, communication and database problems. Present research efforts investigate these complexities only within their respective areas and essentially ignore the interactions with other areas. The Robotic Testbed Facility within the Center for Intelligent Robotic Systems for Space Exploration is a good example of a complex system with numerous interactions that affect overall performance.

This testbed facility consists of three SUN stations, two PUMA arms mounted on a moving platform, and sensors providing vision, force and tactile information. Off-line planning, on-line planning, image processing and control are all performed in real time. The problem is to analyze this system for its time to respond to a command. This performance analysis is done using Petri Nets. The model for this hierarchical architecture is described and results are presented for the autonomous case.

The model is then modified to include a human in the loop representing a shared control mode. The response time of the combined human/robot system is then re-evaluated.

PROJECT 14: Modeling and Analysis of Multiple Arms on a Mobile Platform
S. Murphy and G.N. Saridis

When a robot manipulator is placed on a platform which may have unconstrained degrees of freedom, the motion and position of the manipulator will affect the control of the platform. Likewise, the motion of the platform will affect the manipulator control. The research efforts have concentrated on the control and analysis problem associated with multiple robot manipulators on a mobile platform. The work has been divided in to the cooperation on a fixed platform and cooperation on the mobile platform.

Using efficient forward dynamic calculation methods, a complete MATLAB simulation of two six degree of freedom cooperating robot manipulators on a fixed platform was established. The simulated system was controlled using the recent methods developed at Rensselaer Polytechnic Institute and Jet Propulsion Laboratory for the control cooperating multiple manipulators. The visualization of the motion and the wire-frame modeling of the system was presented through the SILMA Cimstation modeler. Further work developed the formulation of the dynamics for cooperative manipulators on the mobile platform and the simulation/visualization of the arms and platform.

Other issues that are currently under active investigation are:

- Examining the effects of force sensor bandwidth limitations on the control of street forces and load mass compensation.

- Including the effects of gear rations, friction and stiction into the simulation models in an accurate and efficient manner.

- Evaluation of multiple-arm control methods through the simulation environment.

PROJECT 15: Multiple-Arm Manipulation with Multiple-DOF Contacts and Internal Payload DOF
J.T. Wen

The control structure developed for multiple-arm manipulation with rigid payload and rigid grasp has been generalized to payloads interconnected rigid components (such as scissors and pliers) and to multiple degrees-of-freedom grasps (such as point contact, point contact with friction, soft finger, sliding, etc.). The move/squeeze decomposition is generalized to both cases and can be exploited to decouple the position and force control problems. In the multiple-DOF contact case, the decomposition is for the contact force subspace due to the contact constraint. In the case of payloads consisting of interconnected rigid bodies, the decomposition is for the contact force subspace due to the interconnection constraint in the payload. The next stage of generalization is to payloads that exhibit structural flexibility.

PROJECT 16: Force Control
J.T. Wen

The force control problem is investigated from several viewpoints: unmodeled external force as a disturbance, compliance to unmodeled but bounded external force, and compliance to the force of interaction with a generalized mass-spring-damper environment. In the first case, the energy Lyapunov function approach is applied to characterize the position error as a function of the disturbance force. In the second case, stability of a general compliant control scheme is proved. In the last case, the stability of position accommodation type of control law is shown critically dependent on the ratio of the environmental stiffness and the desired damping, which acts as the integral gain in a third order system. This result explains the force control experiments in which response is stable for large desired damping and stiff environment, and small desired damping and soft environment, and unstable (or oscillatory) for small desired damping and soft environment, and large desired damping and stiff environment. This is in contrast to the existing explanation of the instability phenomenon based on the noise disturbance in the high frequency range.

PROJECT 17: Unified Framework for Robot Control

J.T. Wen

By using the Lyapunov analysis motivated by the consideration of the total energy in the system, a large family of robot control laws has been developed. This family shares the basic structure of feedback plus feedforward terms. The role of the feedback term is for stable tracking and disturbance rejection, and the feedforward term is for enhancing the tracking performance by compensating for the model dynamics. By considering different feedforward compensations, this family exhibits a hierarchy in the order of controller complexity. The feedforward can be zero which incurs a tracking error but does not require much model information, it can be model-based which achieves perfect tracking in the noise-free case, or it can be model-based with parameter adaptation which only requires the *structure* of the model but not the exact parameter values. This family demonstrates the classic trade-offs between the amount of a priori model information, robustness with respect to the model information, achievable tracking performance, sensitivity with respect to external disturbances and implementation complexity. Since both exact compensation and partial compensation can be considered, the open loop linearization and nonlinear model-based approaches, which are traditionally regarded as two dichotomous avenues, are analyzed in a single unifying framework. This structure also suggests natural extensions to using learning algorithms for the feedforward term.

PROJECT 18: Attitude Control
J.T. Wen

When the robot control objective is posed in the task coordinate, the attitude (or orientation) control of the arm effector and the payload becomes an important issue. The two important considerations are the selection of error measure and the choice of representation of the rotation group. By combining the globally non-singular unit quarternion representation, the relative frame error, and the energy Lyapunov function technique, a large class of *globally* asymptotically stable attitude control laws is derived. This is one of the first algorithms for which the global stability has been shown. In this framework, the linearization-based Luh-Walker-Paul algorithm is shown to almost globally asymptotic stable, but suffers from poor performance in large angle maneuvers.

E. ADAPTIVE AND LEARNING CONTROL

PROJECT 19: Adaptive and Learning Control
H. Kaufman, D. Minnick and G. Neat

Many direct and indirect adaptive control methods have been developed to regulate processes with large uncertainty in parameters and/or whose parameters vary over a wide range. These methods may fail when the process varies in such a manner that the sufficiency conditions under which they were applied become invalid. For plants such as this, the next stage in the evolution of a control structure would be the combination of a range of algorithms to address the possible structure variation undergone by the plant. This type of controller which expands the capabilities of conventional controllers, requires a supervisor or expert to orchestrate the controllers as the conditions of the process change. Expert control concepts have been introduced previously to coordinate parameter adaptive control methods.

The approach taken here is to extend the concept of expert control to a broad range of plants without the need for parameter estimation, in particular, a six degree of freedom robot arm with a varying payload. The heuristic decisions needed to regulate the control structure from a coarse control to a fine tuning control are made by the expert system as it learns about the plant. The controller bank consists of a multiple model adaptive controller (MMAC) and a model reference adaptive controller (MRAC).

The major contributions of this work involve combining the above mentioned controllers in order to regulate MIMO robotic processes exhibiting a variable structure. Either of the controllers in the controller bank operating individually in regulating such a process may fail or become too unreasonable to implement. The MMAC in this situation could conceivably require an exorbinant amount of models to perform an adequate control job. The MRAC alone requires stringent sufficient conditions that may be the combination of the above mentioned controllers in a dependent fashion in order to provide satisfactory control while overcoming the shortcomings of the individual controllers.

The performance of the hybrid controller has been tested in simulations by comparing its regulatory abilities with the individual controllers that makeup its structure in the motion control of a six degree of freedom robot arm.

The model-controller bank consists of two model-controller pairs. Each model is designed for a given arm configuration and payload. The maximum payload that the robot is expected to carry is eight pounds. In order to span the entire range of expected payload variations, one model-controller is designed for the no payload case while the other model-controller is designed based upon the arm carrying the maximum load of eight pounds.

Each model-controller provides satisfactory control when the actual payload matches its designed payload. The performance of the controller degrades as the difference between the actual payload and the designed payload increases.

The MMAC control weights reach steady state values proportional to how closely their associated models match the actual plant. The control weight associated with the eight pound model-controller converges to approximately one while the zero pound model-controller weight factor approaches zero. The improvement in the tracking performance of the controller is directly related to the adjustment of the control weights.

Future work includes adding a fuzzy controller to the controller bank to provide initial control while the weighting factors reach a steady state value and also to provide backup control in the case of instability in the model based approaches.

F. RELIABILITY AND SAFETY

PROJECT 20: Expert Aided Adaptive Control
L.K. Lauderbaugh and G. Sullivan

Practical problems with adaptive controllers (measurement noise, low excitation, etc.), require "safety nets" be added to adaptive controllers to make them run properly. Traditionally safety nets have been implemented with procedural programming techniques, and lack the ability to reason about problems or plan solutions. With advent of expert systems technology, it is now possible to enhance the functions of the safety net, allowing true diagnosis and treatment of problems with the adaptive controller. In the following discussion, work on an expert aided adaptive controller called the A/E controller is presented. We begin with a brief description of the A/E controller and then conclude with a summary of the accomplishments to date.

Overview of the A/E Controller. The A/E controller consists of four main pieces: an adaptive controller, the signal-to-symbol interface, the symbol-to-procedure interface and the expert system module. The signal-to-symbol interface gathers data from the adaptive controller over a constant time period called the expert system sampling interval and converts this data to symbolic phrases that describe the state of the adaptive controller. At the end of each expert system sampling interval, the expert system module polls the signal-to-symbol interface and receives a symbolic description of the adaptive controller. Using the information in its knowledge base, the expert system module diagnoses problems with the adaptive controller and then formulates a schedule containing the names of procedures that will be used to enhance the performance of the adaptive controller. The last step in the A/E controller cycle is performed by the signal-to-procedure interface, which activates the procedures listed on the schedule as starting times arrive.

Status of Work. At the time of the last progress report (January 1989), a prototype of the A/E controller had been tested, and several areas for further work were identified:

1. Upgrading the expert system facility.
2. Finalization of scheduling algorithms.
3. Development of additional procedures to aid the adaptive controllers.

In the past six months we have made progress on improvements to the expert system facility and the development of scheduling algorithms. Specifically, a formal grammar has been developed for the Expert System Module that allows functions which execute immediately, delayed execution functions and temporal relations for use in knowledge representation. The scheduling facility for the expert system module is now complete and includes several important functions:

1. Produces schedules with no interference between the controlled variables of the procedures on the schedule.
2. Places procedures on the schedule so that results of procedures are available at the correct times.
3. Allows sequences of procedures to be defined and scheduled in order.

In addition to these accomplishments, forward chaining has been added to the system, and an expert system management program has been developed. The end result is that the expert system module is capable of dealing with time varying facts, and can manage a diagnostic/treatment process that evolves with time. Future work will concentrate on development and finalization of the signal processing algorithms in use by the A/E controller.

PROJECT 21: Robot Safety Study
L.K. Lauderbaugh and P. Gray

Terrestrial operation of autonomous robots, with their unfamiliar and often unpredictable movements and extended range of motion, has resulted in the creation of new safety hazards to add to the long list of risks associated with the operation of traditional industrial machines. To these safety hazards we will soon add hazards associated with the employment of robots in space operations. A major goals of the research conducted at Rensselaer from September 1987 through December 1988 was to satisfy the need for structure in the study of robot safety, and apply this structure to the study of space robot safety. Since December the robot safety study has had a change in personnel. Ms. Montgomery has finished her studies and decided to leave RPI. She will be replaced by Patricia Gray. With this change, much of the effort in this area has focused on familiarizing Ms. Gray with the previous work on this project. Ms. Gray will be up to speed and will formally begin her work on this project in September 1989.

In addition to bringing on a new person, we have been working on two primary problems in this study. The first of these has been the further identification of "experts" in the application of robot safety to space based system. This identification has occurred via discussions with various NASA Centers and industrial contacts. The second problem being addressed is the development of experimental systems to be used for design and evaluation of safety systems.

Two experimental facilities are being developed. The primary testbed for the safety systems will be on the demo project. In the experiments using the demo project we will have access to sensor motion and control information. This information will be used to evaluate the performance of various safety systems and approaches.

The second experimental system under development provides a smaller scale, repeatable testbed to be used for development of safety algorithms and approaches. This second experimental system is described in the next section.

PROJECT 22: Safety Control

L.K. Lauderbaugh and V. Ree

Research is being conducted into the development of an automatic control system whose objective is to optimize the safety of an automated system during operation. There are three major questions being addressed:

1. How do we measure the levels of safety, risk, cost, etc., such that safety control can be accomplished?

2. In addition, what peripheral criteria, attributes (including states and outputs of the system and its environment), goals and objectives need to be established and measured for the safe control of the system? Moreover, how are decisions involving safety to be made, and what is the appropriate level of safety?

3. How should the control system be structured and operate to best meet its objectives and goals, i.e., what's an appropriate architecture?

There are many different sources of information concerning the issues of measuring risk and safety including those from (industrial) safety engineering, portfolio analysis in economics, and decision making. Unfortunately, most of these are insufficiently precise for use in the development of a safety controller.

The concensus opinion is that there are at least two factors involving risk and safety. First, a measure of the "degree of hazard" that is, its seriousness. Second, the costliness of the hazard needs to be assessed which includes the effort that is needed and time involved; there needs to be a "justification factor" so that an overall hazard priority rating scheme can be developed for decisions involving safety and risk. However, when making such decisions, other factors also must be weighed into the problem including the performance demands placed on the system which are usually dynamic in nature. Therefore, safety and performance are potentially conflicting objectives and need to be properly weighed.

The mathematical definition of Risk and Priority we are currently working with is:

$$\text{Risk (Threat)} = P\,[\text{Threat being executed}] \; {}^{*}P\,[\text{Damage}|\text{Threat has been executed}] \; {}^{*}\text{Damage}$$

$$\text{Priority (Threat)} = \text{Solvability (Threat)/Risk (Threat)}$$

Here, we define a threat as the expression of a hazard to do harm or damage, the hazard being a source of threats. We are assuming that damage can be measured using the principles of utility theory. Solvability is a measure of the effort in dissolving a threat to safety. Safety threats are dissolved in order according to their priority; the lower a threat's priority number, the earlier it is dissolved (the "higher" its priority).

Safety is a function of Risk and of the context of the system's operating and environmental conditions. Therefore, the factors affecting the safe operation of the system are context dependent as well. In addition, depending upon the complexity and design specifications of the system, the actual implementation of its safety controller may vary from a simple automatic controller to an adaptive controller, decision support system, or an expert-aided intelligent controller.

An appropriate benchmark problem for a safety control system would be one involving collision avoidance. We are designing an experiment that would involve a mobile robot and moving obstacles in its environment. A brief description of the experiment follows.

A mobile robot has the task of traversing a room without colliding into any obstacles in its environment with the additional proviso that the task be accomplished in a certain time period. The two potentially conflicting goals of the robot are that it complete its task in the time allotted, but it must do so safely. By adjusting the available time period for task completion, the level of safety, and task importance, the robot will take different courses of action in accomplishing its goals.

Hypothetically, safety and task importance are inversely proportional; if the importance of the satisfaction of goals involving task performance is increased, safety may be compromised and vice versa. Similarly, safety and completion time are inversely proportional. In this experiment, the task is either completed or not and the only continuous variable is completion time. Therefore, to simplify the experiment, task importance might be measured using completion time; the robot's objective being to minimize completion time. The reason for this is that for more complex tasks, other performance measures might be used to gauge task importance and completion time might be inversely proportional to task importance, i.e., "quality versus deadline" as in industry.

G. PARALLEL COMPUTATION AND INFORMATION MANAGEMENT

PROJECT 23: Three-Dimensional Sensing and Scene Interpretation

L.A. Gerhardt and F. Miller

Over the last period, a three-dimensional vision simulation package (VSP) has been developed. This software package, now run on our SUN system and allows the performance of an arbitrary arrangement of two or more cameras to be evaluated based on stereoscopic accuracy and responses to disturbances. In this manner the responses of a three-dimensional point in space as affected by camera motion can be analyzed and compensation means optimally designed. Results can be evaluated for both a single experiment and also a suite of experiments. Camera disturbances can be expressed explicitly using a list of constants or in terms of function generators which can provide calculated polynomial and Gaussian inputs. Post processing functions are available to help characterize the disturbance response.

The system's operation has now been verified with a number of test cases. The simple test cases have also been verified by a closed form analysis, and overall, these have built confidence in this simulation system and helped gain insight into the underlying mechanisms regarding the effect of stereoscopic vision subject to disturbances. For the more complex cases, the simulation is the only alternative since the analytical solution is beyond a closed solution.

Results are presented as three-dimensional points representing a probability density function. Experimentation was done using a mesh display and isodensity contours using filtered data, but these did not clearly illustrate the results as well as the density or "cloud" display. Three-dimensional density also incorporates an optional projection onto different planes of the viewing cube.

This allows an interpretation of the data with respect to different parameters to maximize separability.

A number of improvements to the system are under consideration. These include:

- Add a time variable so that a dynamic display can be supported for non-stationary disturbance functions.
- Increase emphasis on sinusoidal disturbance functions of the type to be generated by the demonstration\testbed setup.
- Add capability to support interpretation of structured light used in illuminating the 3D object.
- Simulate the resolution capabilities of the camera so that the effect of camera resolution on overall system performance can be determined.

For the next period, it is our intention to begin building this three-dimensional sensing system to be integrated with the testbed demonstration. RPI has extensive experience in this type of system using stereoscopic ranging with laser augmentation. As a result, our efforts will be on making the system efficient, small, and high-speed with respect to computation. Existing software is available for auto calibration, the basic ranging algorithm, and other interface functions.

During this period, serious interest was expressed regarding a possibility of incorporating eye-tracking research into the NASA program. We have had extensive experience in this area and have previously developed a stand-alone eye-tracking system for a wide variety of applications. The usefulness of an eye-tracking system for establishing prioritization of visual ques and understanding astronauts reactions to different environmental situations would be an invaluable addition to the program. Some specific examples demonstrating the potential usefulness of such a system as suggested by other PI's on the project appear below.

In the progression from teleoperated systems to fully autonomous systems, shared control of robotic machines represents a reasonable way to relieve the human operator of tedious routine operations while maintaining ultimate supervisory and backup control of the machine. The use of eye-tracking techniques could potentially allow for rapid human input to such systems. A study of the solutions provided by human beings could lead to heuristics which could provide reasonable on-time solutions to complex unanticipated problems.

Current approaches to the planning of a path from an autonomous vehicle are appropriate for warehouse and detailed scenarios. However, new approaches are needed for the exploration of and traveling through unknown environments. Observation of human operators in performing a variety of vehicle navigation tasks could provide insight on how such sensing strategies might be organized and employed.

In a similar situation, the sensing strategies employed by humans when performing tasks like the assembly of truss structures could provide insight on the organization of sensing strategies for similar tasks to be performed by autonomous machines. Eye-tracking data could provide confirmation for existing biologically motivated approaches found in the literature.

As such it is our intention to also investigate the development of a small real-time eye-tracking system using as much of off-the-shelf hardware as possible, so as to provide an adjunct for the scene interpretation aspects of this task.

The combination of the visual simulation package, the actual 3-D measurement system, and the eye-tracking capability should provide a unique composite and methodology for doing three-dimensional sensing and scene analysis, combining the values of human and machine interaction.

H. EXPERIMENTAL FACILITY

PROJECT 24: Testbed Project Progress Report
K. Walter

The Testbed will provide CIRSSE with a facility where experimentation and demonstration of the varous research projects can take place. This project will be divided into four major categories: Computer Systems, Real-Time Control System, Vision Systems and Robot Transporter. Each of these areas will be discussed in detail. A CIRSSE NASA Lab configuration diagram is included at the end of this section as Figure H-1.

Computer Systems
K. Walter

All of the computer systems shown below are installed and networked through TCP/IP ThinNet.

- SUN 4/260HM
  - File/Computer Server to CIRSSE Local Network
  - Gateway to RPI Campus Network
- SUN 3/260C
  - Host to 3D Vision System
- SUN 3/150M
  - Host to Real-Time Control System
- SUN 3/60C
  - Program Development Workstation
  - SILMA (CAD Simulation Package) Workstation
- VAX 11/750
  - Terminal Server
  - X-Window Development Platform

Equipment is currently on order to upgrade and improve the performance of some of the above systems. A 327MB disk and 4MB of additional memory will be added to the SUN 3/150M (RTC system host), an additional 892MB disk will be added to the SUN4/260HM file server, and 8MB of additional memory will be added to the SUN 2/60C to enable faster SILMA simulations.

A problem that we have run into lately is that many of our current applications software packages make use of high-resolution graphical displays, and we have very limited workstation availability. As a solution to this, we have installed an X-window environment on the VAX 750 for evaluation of X display terminals. Our current plans are to add up to six X-terminals to the CIRSSE facilities this year to alleviate the workstation shortage.

Real-Time Control System

K. Walter

VxWorks (Version 4.0.2) has been installed as a development tool for the real-time control software. The VME system has been set up with a minimal configuration of one MVME-135 68020 processor, an MVME-330 Ethernet controller and one MVME-340A Parallel I/O board. A VxWorks driver for the PIO board was written by lab personnel, and is currently being tested and debugged. A FIFO interface was designed, tested and debugged. This interface connects the PIO in the VME system with the DRV-11 in the PUMA controller. Once the driver software is stable and has full interrupt support, control software can be tested that will allow single arm control through this minimal configuration.

A parallel effort is also underway to provide a software driver for an Ironics IV-3201A 68020 CPU which is not currently supported under VxWorks.

Vision Systems

K. Walter

The Sun 3/260C with a TAAC-1 applications accelerator arrived in early February 1989 and the MATROX MVP-S vision system was installed. The MATROX can support up to four monochrome cameras or one color camera at various video standards. This system is currently working with the camera system that previously existed in the lab.

Purchase of the CIRSSE Robot Transporter

S. Murphy, J. Robinson and A.A. Desrochers

The work on locating a robot transporter for the CIRSSE robots was completed with the decision to buy a transporter from Aronson Inc., Arcade, New York. The robot transporter will consist of two three degree of freedom bases upon which will be mounted PUMA manipulators. The bases will be mounted on a common linear rail for the first degree of freedom. Each base will also be capable of independent pan and tilt degrees of freedom.

The specifications for the final transporter are as follows:

- 2 Rotate and Tilt tables with 8 ft. linear motion (single 12 ft. track)
- Approximately 2 ft. x 30 in. carriage base - Top mounting plate with holes to meet PUMA specifications
- Optical encoders mounted on each servo motor
- Tach generator on each servo motor
- Current loop controller will be implemented for each motor
- Weight: Approximately 5,000 lbs. (Track - 1,000 lbs., Tables - 2000 lbs. each)
- Passive brakes - Power off, brakes on
- Ability to bolt and move the two tables together

The motion, speed and angle measurement requires for the tables are shown in Table H-1.

Tilt/Rotation	Max Velocity	Measurement Accuracy
rotation: ±150°	10-20 deg/sec (1.5-3 rpm)	5.0×10^{-3}deg (18 arc seconds)
tilt: ±45°	10-20 deg/sec (1.5-3 rpm)	5.0×10^{-3}deg (18 arc seconds)

Table H-1. Desired Rotational Specifications

The linear motion of the tables will be provided through two carriages mounted on single rail. Each carriage is free to move independently of the other. Table H-2 presents the specifications for the linear motion.

Length	Carriage Velocity	Position Resolution
12 ft	12-24 in/sec	0.2mm

Table H-2. Linear Motion Specifications

NASA Lab Configuration

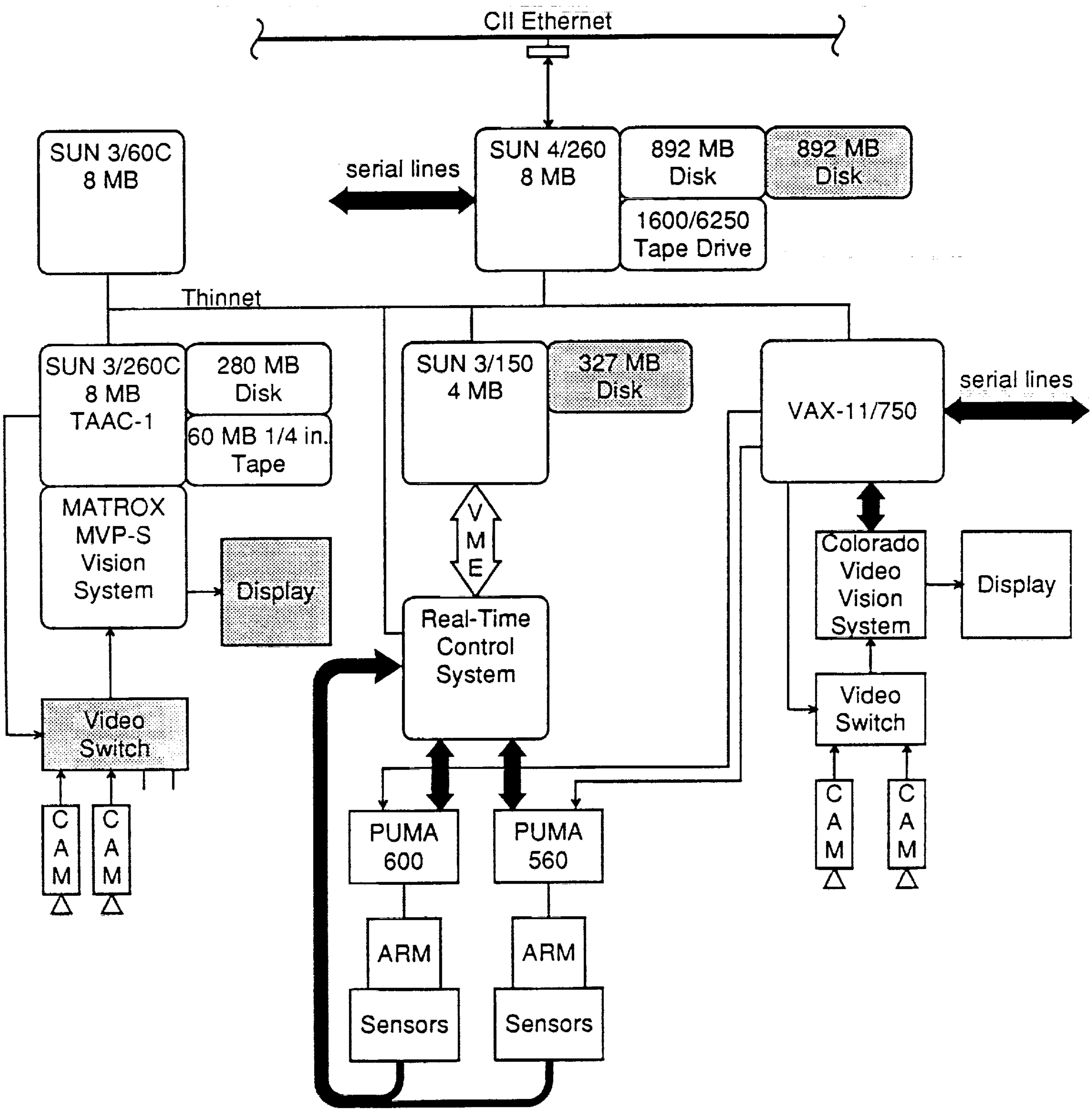


Figure H-1 NASA Lab Configuration

III. FACULTY, STUDENTS AND STAFF

A. FACULTY

George N. Saridis, Professor of Electrical, Computer and Systems Engineering and Director of CIRSSE; intelligent control systems, pattern recognition, computer systems, robotics, prostheses.

Stephen J. Derby, Associate Professor of Mechanical Engineering, Aeronautical Engineering and Mechanics; mechanisms, kinematics and robotics, computer graphics, design.

Alan A. Desrochers, Associate Professor of Electrical, Computer and Systems Engineering; Associate Director of CIRSSE; nonlinear systems, robotics, control of automated manufacturing systems.

Lester A. Gerhardt, Professor of Electrical, Computer and Systems Engineering and Computer Science; communication systems, sensor technology and integration, interactive computer graphics, digital voice and image processing, adaptive systems, pattern recognition and computer integrated manufacturing.

Howard Kaufman, Professor of Electrical, Computer and Systems Engineering; digital control systems, adaptive systems applications and theory, optimal control.

Robert B. Kelley, Professor of Electrical, Computer and Systems Engineering; robotic systems, machine intelligence, machine vision, expert systems.

L. Kenny Lauderbaugh, Assistant Professor of Mechanical Engineering, Aeronautical Engineering and Mechanics; automatic control, manufacturing.

Arthur C. Sanderson, Professor and Chairman of Electrical, Computer and Systems Engineering; robotics, knowledge-based systems, computer vision.

C.N. Shen, Active Professor Emeritus of Electrical, Computer and Systems Engineering; navigation of mobile robots, laser ranging systems.

John T. Wen, Assistant Professor of Electrical, Computer and Systems Engineering; multiple-arm manipulation and control, distributed parameter systems.

B. STUDENTS

1. Graduate Students

- X.Chen
- W.Y. Chen
- C.H. Chung
- K. Damour
- T. DeLaRosa
- P. Gray
- P. Hill
- D. Hughes
- S. Krishnan
- K. Kyriakopoulos
- R. Mathur
- J. McInroy
- S. Miller
- D. Minnick
- M. Mittman
- M.C. Moed
- S. Murphy
- J. Musto
- G. Neat
- J. Newcomer
- J.R. Noseworthy
- L. Page
- B. Ravichandran
- V. Ree
- M. Repko
- J. Robinson
- E. Simpson
- D. Sood
- J. Sullivan
- T. Tsolkas
- F.Y. Wang
- J. Watson
- H. Welch
- L. Wilfinger
- H. Zhang

2. Undergraduate Students

- L. Carmichael
- S. Sekelsky
- K. Singletary
- E.J. Whitehead

C. ADMINISTRATIVE AND TECHNICAL STAFF

- Judi Bloomingdale - Administrative Assistant
- Betty Lawson - Senior Secretary
- Keith Fieldhouse - Software Engineer
- Ken Walter - Research Engineer

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IV. VISITS - JANUARY 1989 TO PRESENT

A. ON-CAMPUS VISITS

1. March 1989 - Dr. M. Fan, Research Professor in Electrical Engineering Department, University of Maryland at College Park.
2. April 1989 - Professor L. Huang, Visiting Professor in Electrical Engineering Department, University of Massachusetts.
3. April 1989 - Dr. S.E. Salcudean, IBM Watson Research Center, Yorktown Heights, New York.

B. OFF-CAMPUS VISITS

1. June 1, 1989 - J.T. Wen visited IBM Watson Research Center, Yorktown Heights, New York.
2. July 17, 1989 - H. Kaufman visited Kennedy Space Flight Center, Florida.
3. July 20, 1989 - A.A. Desrochers, R.B. Kelley and A.C. Sanderson visited NASA Langley Research Center, Hampton, Virginia.

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V. PUBLICATIONS - JANUARY 1989 - PRESENT

A. JOURNAL ARTICLES

1. L.A. Gerhardt (Principal Author and Chairman), "Advanced Robotics for Air Force Operations", National Academy Press, May 1989.

2. Kelley, R.B., "Integrated Sensing for Circuit Board Insertion", Journal of Robotic Systems, special issue on mutlisensor integration and fusion, December 1989 (in press).

3. Leahy, M.B., G.N. Saridis and K.P. Valavanis, "Evaluation of Dynamic Models for Robot Control", IEEE Journal of Robotics and Automation, Vol. 5, April 1989, pp. 242-245.

4. Leahy, M.B. and G.N. Saridis, "Compensation of Industrial Manipulator Dynamics", International Journal of Robotics Research, Vol. 8, No. 4, August 1989, pp. 73-84.

5. Montgomery, T.D. and L.K. Lauderbaugh, "Robots in Space - A Checklist for Safe Design and Operation", SME Technical Paper #MS89-128.

6. Sanderson, A.C. and L.S. Homem de Mello, "Assembly Sequence Planning", Artificial Intelligence Magazine, Invited Paper, special issue on assembly planning, August 1989.

7. Saridis, G.N., "An Analytic Formulation of IPDI", Automatica, The IFAC Journal, Vol. 34, No. 3, May 1989, pp. 461-467.

8. Saridis, G.N., "Correction to Entropy Formulation of Optimal and Adaptive Control", IEEE Transactions on Automatic Control, Vol. 34, No. 6, June 1989, p. 672.

9. Wang, F. and G.N. Saridis, "A Coordination Theory for Intelligent Machines", Accepted by Automatica.

B. CONFERENCE PROCEEDINGS

1. Baartman, J., A. Brennemann, S. Buckley and M.C. Moed, "Using Coarse-Fine Manipulation with Vision to Place Fine Pitch SMD Components", IEEE International Electronics Technology Symposium, San Francisco, CA, September 1989.

2. Bonner, S. and R.B. Kelley, "Planning 3-D Collision-Free Paths Using Spheres", Proceedings of the 1989 NASA Space Telerobotics Conference, Pasadena, CA, January/February 1989 (in press)

3. Bonner, S. and R.B. Kelley, "Planning 3-D Collision-Free Paths", Proceedings of the Fourth IEEE International Symposium on Intelligent Control, Albany, NY, September 1989 (in press).

4. Chung, C.H. and G.N. Saridis, "The Recursive Compensation Algorithm for Obstacle Avoidance Path Planning, Proceedings of the Workshop on Intelligent Robots and Systems, 1989, Tsukuba, Japan, September 4-6, 1989.

5. Chung, C.H. and G.N. Saridis, "Path Planning for an Intelligent Robot by the Extended VGraph Algorithms", Proceedings of the Fourth IEEE International Symposium on Intelligent Control, Albany, NY, September 1989.

6. L.A. Gerhardt, "The Status of Mobile Robots in Western Europe", Robotics and Automation Conference, Scottsdale, Arizona, May 1989.

7. Kaufman, H., D. Minnick and G. Neat, "Development and Applications of an Expert Hierarchical Model Reference Adaptive Controller", IASTED International Conference on Adaptive Knowledge Based Control and Signal Processing, Honolulu, HI, August 16-18, 1989.

8. Kelley, R.B. "Inspection of Twisted Wire Brushes: A Case Study", Proceedings of RI/SME 1989 World Conference on Robotics Research, Gaithersburg, MD, May 1989, pp. 5-43:54.

9. Minnick, D., H. Kaufman, and G. Neat, "Expert Hierarchical Adaptive Control for Robotic Systems", Proceedings of the Fourth IEEE International Symposium on Intelligent Control, Albany, NY, September 1989.

10. Moed, M.C. and G. Saridis, "A Boltzmann Machine for the Organization of Intelligent Machines", Proceedings of the NASA Conference on Telerobotics, Pasadena, CA, January 1989.

11. Saridis, G.N., "On the Revised Theory of Intelligent Machines", Proceedings of the International Workshop on Intelligent Robots and Systems, 1989, Tsukuba, Japan, September 4-6, 1989.

12. Shen, C.N. and G. Nagy, "Autonomous Navigation to Provide Long-Distance Service Traverses for Mars Rover Sample Return Mission", Proceedings of the Fourth IEEE International Symposium on Intelligent Control, Albany, NY, September 1989.

13. Sood, D., M. Repko and R.B. Kelley, "Using Multiple Sensors for Printed Circuit Board Insertion", Proceedings of the 1989 NASA Space Telerobotics Conference, Pasadena, CA, January/February 1989 (in press).

14. Sood, D., M. Repko and R.B. Kelley, "Design and Implementation of a Multi-Sensor Robot System for Printed Circuit Board Insertion", Proceedings of the IEEE International Conference on Robotics and Automation, Scottsdale, AZ, May 1989, pp. 377-382.

15. Wang, F. and G.N. Saridis, "The Coordination of Intelligent Robots: A Case Study", Proceedings of the Fourth IEEE International Symposium on Intelligent Control, Albany, NY, September 1989.

16. Wen, J.T. and K. Kreutz, "Stability Analysis of Multiple-Robot Control Systems", Second NASA/JPL Telerobotics Conference, Pasadena, CA, January 1989.

17. Wen, J.T. "The Energy Lyapunov Function Approach to Robot Control" Workshop on Nonlinear and Adaptive Control of Robots, Merida, Mexico, May 10, 1989.

18. Wen, J.T. and K. Kreutz, "Motion and Force Control of Multiple Cooperative Manipulators", 1989 IEEE Robotics and Automation Conference, Scottsdale, AZ, May 1989.

19. Wen, J.T., "Finite Dimensional Controller Design for Infinite Dimensional Systems: A Passivity Approach", Proceedings of 1989 American Control Conference, Pittsburgh, PA, June 1989.

20. Zhang, H., A.C. Sanderson and L.S. Homem de Mello, "Generation of Precedence Relations for Mechanical Assembly Sequences", IEEE Fourth International Symposium on Intelligent Control, Albany, NY, September 1989.

C. BOOKS

1. Desrochers, A.A., Modeling and Control of Automated Manufacturing Systems, a tutorial text under contract with the IEEE Computer Society Press, Spring 1989.

2. Saridis, G.N., Editor, Advances in Automation and Robotics, Vol. 2, JAI Press, Spring 1990.

3. Saridis, G.N. and H. Stephanou, Editors, "Knowledge Based Systems for Intelligent Machines", Springer Verlag (NATO ASI Senses), Spring 1990.

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14. Montgomery and L.K. Lauderbaugh, T.D., "A Matrix Safety Frame Approach to Robot Safety for Space Applications", December 1988.

15. Wang, F.Y. and G.N. Saridis, "A Coordination Model for Intelligent Machines", January 1989.

16. Bonner, S. and R.B. Kelley, "Planning 3-D Collision-Free Paths Using Spheres", January 1989.

17. Sood, D., M.C. Repko and R.B. Kelley, "Using Multiple Sensors for Printed Circuit Board Insertion", January 1989.

18. Neat, G.W. and H. Kaufman, "A Hybrid Adaptive Approach for Drug Delivery System", February 1989.

19. Kyriakopoulos and G.N. Saridis, "An Efficient Minimum Distance Collision Estimation Techniques for On-Line Motion Planning for Robotic Manipulation", February 1989.

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22. Whitehead, J. and K.J. Kyriakopoulos, "Efficient Implementation of Linear and Quadratic Programming Algorithms for Minimum Distance Estimation Between Solids", May 1989.

23. Saridis, G.N., "On the Revised Theory of Intelligent Machines", May 1989.

24. McInroy, J.E., "Determining the Position, Velocity, and Angular Velocity of Known Objects in Real-Time Using Vision", May 1989.

25. K.J. Kyriakopoulos and G.N. Saridis, "Minimum Distance Estimation and Collision Prediction Under Uncertainty for On-Line Robotic Motion Planning", July 1989.

26. Kelley, R.B., D. Sood and M.C. Repko, "Integrated Sensing for Circuit Board Insertion", July 1989.

27. Minnick, D.J., H. Kaufman and G.W. Neat, "Expert Hierarchical Adaptive Controller for Robotic Systems", July 1989.

28. Wen, J.T. and X. Chen, "The Optimal Multiplier Method for Nonlinear Robustness Analysis", July 1989.

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30. Sanderson, A.C., "Applications of Neural Networks in Robotics and Automation for Manufacturing", October 1988.

31. Sanderson, A.C. and L.S. Homem de Mello, "Real-Time Planning and Intelligent Control", October 1988.

32. Homem de Mello, L.S. and A.C. Sanderson, "Representations of Mechanical Assembly Sequences", June 1989.

33. Homem de Mello, L.S. and A.C. Sanderson, "A Correct and Complete Algorithm for the Generation of Mechanical Assembly Sequences", June 1989.

34. Zhang, H. and A.C. Sanderson, "Generation of Precedence Relations for Mechanical Assemblies", August 1989.

35. Zhang, H., A.C. Sanderson and L.S. Homem de Mello, "Generation of Precedence Relations for Mechanical Assembly Sequences", September 1989.

36. Sanderson, A.C., H. Zhang and L.S. Homen de Mello, "Assembly Sequence Planning", August 1989.

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